Exploitation of Overlapping Coverage Area for Performance Improvement in Microcellular Communication Systems

by

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INDIAN INSTITUTE OF TECHNOLOGY KANPUR

March, 2000

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A Thesis Submitted
In Partial Fulfillment of the Requirements
For the Degree of
MASTER OF TECHNOLOGY
By
NITIN KUMAR GUPTA

to the
DEPARTMENT OF ELECTRICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR
MARCH, 2000

Certificate

This is to certify that the work contained in the thesis entitled " ***Exploitation of Overlapping Coverage Area for Performance Improvement in Microcellular Communication Systems*** " has been carried out by Nitin Kumar Gupta (Roll No. 9810433) under my supervision and that this work has not been submitted elsewhere for any degree.

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Abstract

In the design of operational wireless network, overlapping coverage area of nearby base stations plays an important role, especially in small-cell high capacity microcellular configurations. Due to overlap some mobile users may have access to multiple base stations. In case of blocking call from these users can be transferred to alternate base station. This is called "directed retry". Although this scheme can be used to decrease the failure probability for overlap users, there are variations in the failure probabilities experienced by overlap and non-overlap users. Channel restriction can be used to balance these probabilities. . Analytical and simulation model for this is studied and examined the advantages gained in terms of reduced forced termination probability and fairness in the call failure probabilities experienced by the users located in different regions. Performance can be further improved if "channel rearrangement" or "directed hand-off" is used along with the channel restriction. Simulation study for this scheme has been done in this thesis. Results indicate that we have more balanced call failure probabilities with channel restriction and channel rearrangement at the cost of increase in mean failure probability at the high load. Substantial improvement in forced termination probability is achieved with channel rearrangement. Finally, we discuss the possibility of scaling down the number of guard channels with channel restriction to achieve the desired effect of reduced forced termination probability.

Dedicated
To
My Parents

Acknowledgement

I would like to express my sincere thanks to Dr. V. Sinha for his invaluable guidance and encouragement during the course of this thesis work. I am heartily thankful to him for the confidence he showed in me. I would also like to thank Dr. V. Sinha, Dr. S. K. Bose, Dr. S. Umesh and Dr. R. K. Bansal who introduced me the fundamentals of Communications.

I would also like to cherish the nice company of my friends Dhaval, Alpna, Bhuwanendra, Praveen, Harish, Rao, Murthy, and Gaurav without, which the life in the lab would have been monotonous. I would not forget the moments spent with Prabhat and Sudeep. I am also grateful to Vineet, Vivek, and Manoj for providing me various kinds of help in the lab during the course of my thesis work.

I must not forget to mention the name Nikhil, my brother, who was always beside me throughout the M.Tech programme. Last but not least I wish to acknowledge the constant encouragement and blessings which my parents gave to me.

-Nitin

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List of Abbreviations

MSC	Mobile Switching Centre
FCA	Fixed Channel Allocattion
DCA	Dynamic Channel Allocation
GoS	Grade of Service
BS	Base station
MS	Mobile station
DECT	Digital European Cordless Telephony
WACS	Wireless Access Communication System
CT-2	Cordless Telephony – 2
GSM	Global System for Mobile Communication
DR	Directed retry
DH	Directed hand-off

Chapter 1

Introduction

1.1 Introduction

Mobile communication systems are already taking precedence over the public switched telephone systems. Mobile systems free the user from being tied to a physical location while involved in the call, retaining a rigid communication address. Mobile communications covers the technologies related to cellular mobile communications systems, satellite mobile, portable hand held systems, cordless telephones and wireless office. This work is primarily concerned with the application to cellular mobile services.

In cellular communication networks, service to the mobile subscribers is provided by the continuous radio coverage of the base stations called cells, which are usually modelled as hexagons for convenience. Communication channels used in one cell are reused in another cell to increase the system capacity, while minimising interference between the cells (co-channel interference) and between neighbour channels (adjacent channel interference). Due to unpredictable nature of the propagation characteristics, coverage regions under different base stations are not disjoint. Hence there are areas, where mobile station (MS) may be served by more than one base stations due to overlapping of the coverage zones. Usually a MS is connected to the base station that gives the best signal quality. However, in the overlapping region, it could be served by alternative base stations if the received signal is higher than a minimum threshold. The overlap may be used to reduce the blocking probability of calls. Calls arising from the overlap area may be redirected to the neighbouring cell if all channels are occupied in the primary cell. Such a scheme is known as "directed retry." The performance will further improve if "directed handoff" is incorporated into the system. Both of these methods have been proposed as a means of improving the network performance in heavy load areas[1].

One of the main issues in cellular systems is that of handoff. Handoff is resorted to when a mobile subscriber crosses a cell boundary during the course of a call. Moving away from the home cell results in deteriorating speech signal quality. The system, under these conditions, then attempts to allocate a new channel in the new cell. This assignment of a new channel is termed handoff. Due to handoff, distribution of the call holding time is not same as the channel occupancy time. This will be cleared in the next chapter.

It is apparent from the above discussion that mobility of a user must be an important parameter for the system design. The mobility model of the user in cellular systems also plays a very important role in the performance evaluation. This decides the distribution of the in cell residence time, which in turn decides the channel occupancy time distribution. We wish to investigate these issues.

1.2 Motivation

The concept of directed retry and directed hand-off or channel rearrangement has been analysed in [1]. In this paper comparison was made among dynamic channel allocation, directed retry (DR), and directed hand-off (DH). Improved system performance had been achieved with DR and DH schemes. A hand-off issue along with the coverage region has been discussed in [2]. Priority access to hand-off was given at the cost of increased new call blocking probability. This is because hand-offs that fail result in interruption in the service. The concept of channel restriction has been introduced in [3], but effect of channel rearrangement has not been considered along with it. In this thesis, we will consider this feature.

1.3 Channel Assignment Strategies

The strategy of assigning channels to cells and to calls is an important feature affecting the efficiency of the cellular systems. A good channel allocation algorithm is one that provide the best spectral efficiency for a specified grade of service (link

quality, probability of new call blocking, probability of forced termination). There are three basic types of channel assignment strategies [6]:

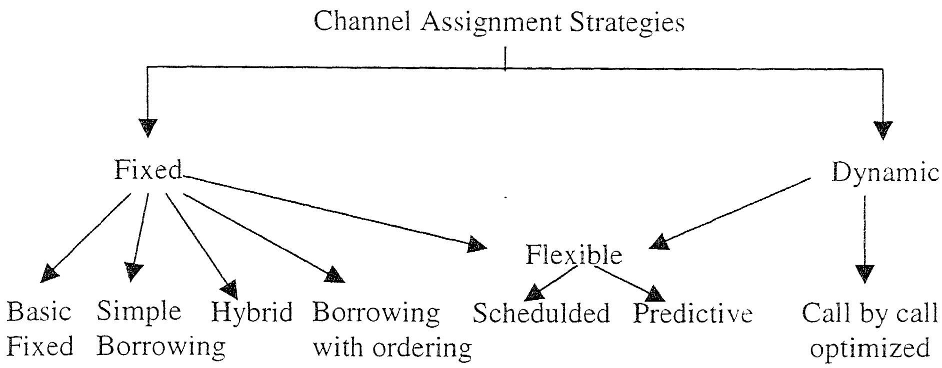


Fig 1.1 Classification of channel allocation strategies

1.3.1 Fixed Channel Assignment

With fixed channel assignment (FCA), each cell is permanently assigned a fixed set of channels. A new call arrival or handoff attempt is blocked if all channels are busy. There are various schemes, such as simple borrowing and hybrid channel assignment, to reduce these blocking probabilities. These schemes have been shown in the fig 1.1. The same set of frequencies is reused by another cell at some distance away. The minimum distance at which radio frequencies can be reused with no interference is called the "co-channel reuse distance".

The basic fixed assignment strategy implies that a call attempt at a cell site can be only served by the unoccupied channels of the predetermined set of channels at that cell site, otherwise the call is blocked. Here, the only role of the MSC is to inform the new BS, and receive a confirmation or rejection message from the new BS, about the hand-off. The MSC keeps track of serving channels for the purpose of updating stored information regarding the location of the MS. Other fixed assignment methods are variations of this strategy.

In the simple borrowing strategy, if all permanent channels of a cell are busy, a channel can be borrowed from a neighbouring cell, provided that this channel does not interfere with the existing calls. When a channel is borrowed, additional cells are prohibited from using it. The MSC supervises the borrowing procedure, following an algorithm that favours channels of cells with the most unoccupied channels to be

borrowed. The algorithm locks the borrowed channel toward the cells that are one or two cell units away from the borrower cells. The MSC keeps record of free, serving and borrowed (hence locked) channels and informs all involved BSs about locked channels. The reward of increased storage requirement at the MSC and the need for database lookups is a lower call blocking probability upto a certain traffic level. In heavy traffic since borrowed channels are locked, channel utilization efficiency is degraded.

This trend is improved by the hybrid channel assignment strategy. In this strategy, permanent channels of a cell are divided into two groups. One group can be used within the cell, the other can be borrowed. The ratio of the numbers of channels in the two groups is determined a priori, depending on the estimation of the traffic conditions. In addition to its duties in the simple borrowing strategy, the MSC (Mobile Switching Centre) has to label all the channels with respect to the group to which they belong.

The borrowing with channel ordering strategy introduces a further improvement on the channel borrowing concept. It elaborates on the idea of hybrid assignment by dynamically varying the local to borrowable channel ratio according to the changing traffic conditions. Each channel has a different adjustable probability of being borrowed and is ranked with respect to this probability, so the channels towards the bottom of the list are more likely to be borrowed, and vice versa. Each time a call is attempted, an algorithm at either the MSC or BS is run to choose the most appropriate channel among all free channels, looking at their associated probabilities. The MSC determines and updates each channel's probability of being borrowed, based on the traffic conditions, by using an adaptive algorithm. The channel assignment strategy can be made more complex by employing intracellular handover or immediate reallocation of a released higher rank channel to a call existing on a lower rank channel. The aim of such reallocation is to reduce the locking effect of borrowed channels in additional cells. Reallocation is invoked each time a channel is freed.

1.3.2 Dynamic Channel Assignment

In contrast to fixed assignment, in dynamic channel assignment strategy cells have no permanent channels to themselves but refer all call attempts to the MSC, which manages all channel assignments in its domain of operation. Each time a call attempt

arrives, the BS asks the MSC for the channel with the minimum cost to be assigned. The cost function depends on the future blocking probability, usage frequency of the candidate channel, the reuse distance of the channel, and so on. The MSC decides on a call by call basis, which channel to be assigned to which call attempt by searching for the available channels for which the cost function is minimum. Naturally, the MSC also takes into account the channel occupancy distributions under current traffic conditions, and other network-directed criteria, as well as radio channel measurements of individual MSs.

1.3.3 Flexible Channel Assignment

Flexible channel assignments combines the aspects of both fixed and dynamic channel assignment schemes. Each cell is assigned a fixed set of channels, but a pool of channel is reserved for flexible assignment. Fixed channels are used under low traffic, while flexible channels are assigned by the MSC to the cells whose permanent channels have become inadequate under increasing traffic load. The assignment of flexible channels can be scheduled or predictive. The flexible channels are assigned to the cells on the scheduled basis to account for those foreseeable changes in the traffic pattern. In the predictive assignment strategy, the traffic intensity, equivalently, the blocking probability is measured periodically at every cell site by the MSC and flexible channels are assigned to the cells according to these measurements. Flexible assignment strategies, like call by call dynamic strategies, require up-to-date information about the traffic pattern in its area and other network-directed criteria in order to manage its set of flexible channels efficiently.

1.4 Hand-offs

Hand-offs are essential in the mobile systems especially when small cell sizes or microcells are employed. Hand-off procedure effects the performance of the cellular systems. There are three strategies for hand-offs.

1.4.1 Mobile Controlled Handoff

Mobile controlled handoff is the most popular technique and is employed by both the DECT (Digital European Cordless Telephony) and the WACS (Wireless Access Communication System) air interface protocols. In this method the MS is continuously monitoring the signal strength and quality from the serving BS and several neighbouring base stations. When some handoff criteria is met the MS checks the best candidate BS for an available traffic channel and launches a handoff request.

1.4.2 Network Controlled Handoff

Network Controlled Handoff is employed by CT-2 Plus. In this method, the BS monitor the signal strength and quality from the MS and when these deteriorate below some threshold, the network arranges for a handoff to another BS [4]. The network asks all the surrounding BS to monitor the signal from the MS and report the measurement results back to the network. The network then chooses suitable BS for the handoff and informs both the MS and the suitable BS. The handoff is then affected.

1.4.3 Mobile Assisted Handoff

Mobile assisted handoff is a variant of network-controlled hand-off where the network asks the MS to measure the signals from surrounding BS and report those measurements back to the serving BS, so that the network can make the determination as to where an handoff is required and to which BS [4]. This handoff strategy is employed by the GSM (Global Systems for Mobile communication) standard.

1.5 Directed Retry & Directed Handoff

Directed retry and directed handoff schemes are alternate schemes between the two extremes of fixed and dynamic channel assignment [1]. These schemes take advantage of the fact that some percentage of the mobile stations may be able to obtain sufficient signal quality from two or more cells as these mobiles may be located in the overlapped regions of the coverage regions of the BSs.

With the directed retry, if a call finds no free channels in its first attempt cell, it then tries for a free channel in any other cell which can provide sufficient signal quality. Directed handoff takes this idea further, in that, when a cell has all or almost all of its channels in use, it may direct some of the calls currently in progress in that cell to attempt to handoff to an adjacent cell. The motivation here is to attempt to rearrange the calls in heavily loaded cells to adjacent cells when these adjacent cells are temporarily carrying a lighter load due to, statistical fluctuations in the cell traffics.

We consider these schemes in this thesis, as improved system performance can be achieved using some of these schemes. This improvement would be dependent on the percentage of calls that can be served by more than one BSs.

1.6 Objective of The Thesis

In a wireless communication network the quality of service indicators such as blocking probability for new calls and communication interruption probability (probability of call dropping) are of high importance. The quality of service perceived by the user is different depending on whether they are in the overlapping region or not. For example if the blocking probability in the nonoverlapping zone is P_b, then the blocking probability in the overlapping zone will be P_b^2 because calls from this region can be directed to the neighbouring cells due to multiple connections to the BSs. In this way a very large variation in the quality of service of the users is experienced depending on the location of the mobile. These blocking probabilities can be balanced through a scheme proposed in this thesis, by restricting the number of available channels for new calls that are made in the overlapping zone. The performance of the system can be further improved if channel rearrangement or so called directed hand-off is considered. Objective of the thesis is to develop analytical and simulation model to exploit the overlapping regions in order to accomplish fairness to all users and to improve the performance of the system.

1.7 Organization of The Thesis

The outline of this thesis is as follows. Chapter 2 discusses the distributions of mobility related parameters that have been considered in thesis. Chapter 3 gives the details about the model description and analysis with the Poisson approximation and IPP(Interrupted Poisson process). Specific algorithm for channel rearrangement, that has been tested, is also discussed in this chapter. Chapter 4 discusses the results and performance of restricting the number of channels available to overflow traffic in the overlapping zones and channel rearrangement. In chapter 5 we will conclude the thesis.

Chapter 2

Traffic Model

Traffic model reflects the actual traffic situation and the user mobility patterns. This chapter deals with characterisation of different mobility related traffic parameters considered in this thesis. These include distributions of the in-cell-residence-time, handoff call cell residence time, the channel-holding-time and average number of handoffs per call.

2.1 Call Holding Time or Unencumbered Session Time

From classical teletraffic theory, it is well known that the call holding time follows a negative exponential distribution. If T_c be the random variable denoting call holding time, probability density function of T_c is given by:

$$\begin{aligned} f_{T_c}(t) &= \mu e^{-\mu t}, \quad \text{for } t \geq 0 \\ &= 0 \quad , \text{ elsewhere} \end{aligned} \tag{2.1}$$

where $\overline{T_c} = \frac{1}{\mu} =$ average call holding time. Due to memoryless property of the exponential distribution, residual message duration after the handoff attempt has the same distribution as that of the unencumbered session time.

2.2 Cell Residence Time Distribution

Depending on whether a call originates in a cell or is handed over from a neighbouring cell, two different cell residence times can be specified. They are new-call-cell- residence-time and hand-off-call-cell- residence time, respectively [5].

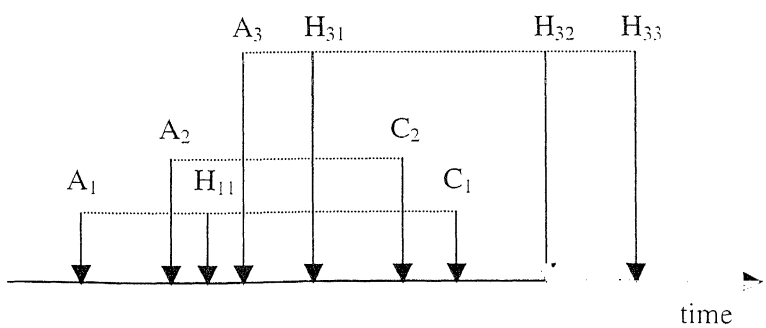
The new call cell residence time is defined as the time between the instant a new call is initiated and the instant the new call moves out of the cell if the new call is

not completed. Similarly the hand-off call cell residence time is defined as the time spent by a mobile in a given cell to which the call was handed over from a neighbouring cell before crossing to another cell. The term "cell residence time" is also labeled as mobile sojourn time or dwell time. Let T_i's be the cell residence time of the mobile in the i^{th} cell when involved in the call. T_i's are independent and identically distributed random variable with pdf $f_{T_i}(t)$ and mean $1/\gamma$.

$$f_{T_i}(t) = \gamma e^{-\gamma t} \quad, t \geq 0$$
$$= 0 \quad , \text{elsewhere} \qquad (2.2)$$

2.3 Channel Holding Time

The channel holding time (or occupancy time) is a random variable defined as the length of time starting from the instant a channel in a cell is seized by the arrival of either a new or a handoff call, until the time the channel is released either by completion of the call or by handing over the call to another cell. In other words, the time spent by a user on a particular channel in a given cell is the channel holding time. The channel holding time is somewhat analogous to the call duration in the fixed telephone network. However, in case of cellular mobile networks, most often it corresponds only to a portion of the total call duration in which the mobile is located in an associated cell. Distribution of this channel holding time depends on the mobility of the users, which can be characterized by the cell residence time.

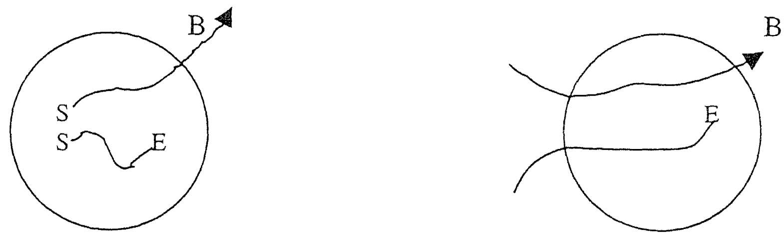


A_i's are the call arrival instants
C_i's are the call departure instants
H_{ij}'s are the j^{th} handoff instants of i^{th} arrival

Fig 2.1 Illustration of different types of handoffs within various call duration

In fig 2.1 time intervals among points (A_1, H_{11}), (A_2, C_2), and (A_3, H_{31}) show the channel holding time for three new calls originating at points A_1, A_2, and A_3. The time intervals between points (H_{11}, C_1), (H_{31}, H_{32}), and (H_{32}, C_3) show the channel holding time for hand-off calls. When a new call is set up, a new call is completed in the originating cell or the mobile moves out of the cell. Therefore the channel holding time of the new call T_N is either T_n (in-cell-residence-time) or T_c(call holding time), whichever is less.

$$T_N = \min (T_n, T_c). \tag{2.3}$$



SB ≡ T_n New call cell residence time AB ≡ T_h Hand-off call cell residence time

SE ≡ Tc Call holding time CE ≡ T_c Residual call time

Fig 2.2 Illustration of the new and hand-off call cell residence time.

By the similar reasoning channel holding time for hand-off call can be given by:

$$T_H = \min (T_h, R_c). \tag{2.4}$$

Where R_c is the residual call duration. Because of the memoryless property of the exponential distribution, R_c can be replaced by T_c.

Let T_n, T_h, T_N, and T_H have the density function $f_n(t)$, $f_h(t)$, $f_{nh}(t)$ and $f_{hh}(t)$ respectively with their corresponding Laplace transforms $f_n^*(s)$, $f_h^*(s)$, $f_{nh}^*(s)$, and $f_{hh}^*(s)$, and corresponding cumulative distribution functions $F_n(t)$, $F_h(t)$, $F_{nh}(t)$, *and* $F_{hh}(t)$, respectively.

From (2.4) $F_{hh}(t)$ can be obtained as:

$$\begin{aligned} F_{hh}(t) &= \Pr(T_H \leq t) \\ &= \Pr(T_c \leq t \ or \ T_h \leq t) \\ &= \Pr(T_c \leq t) + \Pr(T_h \leq t) - \Pr(T_c \leq t).\Pr(T_h \leq t) \end{aligned} \tag{2.5}$$

We have used the independency of T_h and T_c. Differentiating each term in equation (2.5) with respect to t , we obtain

$$f_{hh}(t) = f_c(t) + f_h(t) - f_c(t).Pr(T_h \leq t) - Pr(T_c \leq t).f_h(t)$$

$$= f_c(t).\int_t^{\infty} f_h(\tau)d\tau + f_h(t).\int_t^{\infty} f_c(\tau)d\tau \tag{2.6}$$

Taking Laplace transform of both sides of equation (2.6), we obtain

$$f_{hh}^{*}(s)=\int_0^{\infty}\mu e^{-\mu t}\int_t^{\infty} f_h(\tau)d\tau\, e^{-st}dt+\int_0^{\infty} f_h(t)\int_t^{\infty}\mu e^{-\mu\tau}d\tau\, e^{-st}dt$$

$$=\mu\int_0^{\infty}\left[1-\int_t^{\infty} f_h(\tau)d\tau\right]e^{-(s+\mu)t}dt+\int_0^{\infty} f_h(t)e^{-(s+\mu)t}dt$$

$$=\frac{\mu}{s+\mu}\left(1-f_h^{*}(s+\mu)\right)+f_h^{*}(s+\mu)$$

$$f_{hh}^{*}(s) = \frac{\mu}{s+\mu}+\frac{s}{s+\mu}f_h^{*}(s+\mu) \tag{2.7}$$

By the similar argument $f_{nh}^{*}(s)$ can be written as:

$$f_{nh}^{*}(s) = \frac{\mu}{s+\mu}+\frac{s}{s+\mu}f_n^{*}(s+\mu) \tag{2.8}$$

Expected channel holding times for hand-off and new call are given by:

$$E[T_H] = -f_{hh}^{*(1)}(0) = \frac{1}{\mu}[1-f_h^{*}(\mu)] \tag{2.9}$$

$$E[T_N] = -f_{nh}^{*(1)}(0) = \frac{1}{\mu}[1-f_n^{*}(\mu)] \tag{2.10}$$

Since T_n is the residual life of T_h , distribution of T_n can be obtained from the distribution of T_h by Residual Life Theorem (Appendix A).

$$f_n^{*}(s) = \frac{\gamma[1-f_h^{*}(s)]}{s} \tag{2.11}$$

where $1/\gamma$ is the mean of T_h or mean hand-off call cell residence time.

From (2.11) it can be observed that new call cell residence time is exponentially distributed if hand-off call cell residence time is exponentially distributed with the same mean $1/\gamma$.This can be given in Laplace domain as:

$$f_n^{*}(s)=f_h^{*}(s)=\frac{\gamma}{s+\gamma}$$

Substituting this into (2.7) and (2.8), we can obtain the channel holding time distribution:

$$f_{hh}^{*}(s) = f_{nh}^{*}(s) = \frac{\mu}{s+\mu}+\frac{\gamma s}{(s+\mu)(s+\mu+\gamma)}=\frac{\mu+\gamma}{s+\mu+\gamma} \tag{2.12}$$

This implies that the new call channel holding time is exponentially distributed with parameter $(\mu+\gamma)$.

2.4 Mean Number of Hand-offs

A mobile can move through several cells while being involved in a call. The number of times a mobile crosses different boundaries during a call is a random variable dependent on the cell size, call holding time, and mobility parameters. Each hand-off requires network resources to reroute the call through a new base station. It is preferred to reroute as few hand-off as possible in order to alleviate the switching load and to decrease the processing burden required on the system. The number of hand-offs has a lower bound, which is equal to the number of boundary crossings a mobile undergoes. As the number of hand-offs increases, the hand-off decision algorithms need to be enhanced so that the perceived QoS does not deteriorate.

The mean number of times a nonblocked call is successfully handed over to the neighbor cell during the call can be obtained from [5]:

$$\overline{H} = \sum_{k} k.\Pr\{H = k\} \tag{2.13}$$

where $\Pr\{H = k\}$ is the probability that a nonblocked call crosses k successive cells during its lifetime and H is an integer random variable. Let P_n be the probability that a nonblocked new call will require at least one hand-off before completion and let P_h denote the probability that a nonfailed hand-off call will require at least one more hand-off before completion, and let P_o and P_f denote the new call and hand-off call failure probability.

Consider $\Pr\{H = 0\}$. There will be zero hand-off in two conditions. First when call will not require hand-off. Probability of this is given by $(1 - P_n)$. Second when it will require hand-off and hand-off attempt will be failed at the first visiting cell. Probability of this is given by $P_n.P_f$. Therefore $\Pr\{H = 0\}$ is given by:

$$\Pr\{H=0\} = (1-P_n) + P_n.P_f$$

Similarly $\Pr\{H=1\}$,.........$\Pr\{H = k\}$ are given by:

$$\Pr\{H=1\} = P_n(1-P_o)(1-P_h+P_h.P_f)$$

....

$$\Pr\{H=k\}= P_n(1-P_o)\,[P_h(1-P_f)]^{k-1}.\,(1-P_h+P_h.P_f) \tag{2.14}$$

Substituting (2.14) in (2.15) gives the mean number of hand-offs per call:

$$\overline{H} = \sum_{k=1}^{\infty} k.P_n(1-P_o)[\,P_h\,(1-P_f)]^{k-1}.(1-P_h+P_h.P_f)$$

$$= \frac{(1-P_o).P_n}{1-P_h(1-P_f)} \tag{2.15}$$

The value of P_n can be obtained as :

$$P_n = \Pr\{T_c > T_n\}$$

$$= \int_0^{\infty} \Pr\left\{T_c > t \middle/ T_n = t\right\} \Pr\{T_n = t\}dt.$$

T_n is mainly dependent on the mobility of the users, and has no influence on the call duration T_c. Therefore

$$P_n = \int_0^{\infty} \Pr\{T_c > t\}.\Pr\{T_n = t\}dt$$

$$= \int_0^{\infty} [1 - F_{T_c}(t)].f_n(t)dt. \tag{2.16}$$

$$= \int_0^{\infty} e^{-\mu t}.f_n(t)dt$$

$$= f_n^*(\mu)$$

Similarly value of P_h can be obtained by the following equation:

$$P_h = \Pr\{T_c > T_h\}$$

$$= \int_0^{\infty} e^{-\mu t}.f_h(t)dt. = f_h^*(\mu) \tag{2.17}$$

From (2.15), (2.16) and (2.17) average no. of handoffs can be written as:

$$\overline{H} = \frac{(1-P_o).f_n^*(\mu)}{1-(1-P_f).f_h^*(\mu)} \tag{2.18}$$

2.5 Handoff call arrival rate

Since each unblocked call initiates $\overline{H}$ handoff calls on the average, the handoff call arrival rate can be obtained [4]:

$$\lambda_h = \lambda\overline{H} = \frac{(1-P_o).\lambda f_n^*(\mu)}{1-(1-P_f)f_h^*(\mu)} \tag{2.19}$$

where λ is the new call arrival rate.

If $f_n(t)$ and $f_h(t)$ are exponentially distributed with parameter γ, then handoff arrival rate can be given as:

$$\lambda_h = \frac{(1-P_o)\gamma.\lambda}{\mu + P_f.\gamma} \tag{2.20}$$

2.6 Probability of call completion

Probability with which the call is completed without being forced termination or blocked is given by the following relation [4]:

$$P_C = \frac{(1-P_o)(1-f_h^*(\mu))}{1-(1-P_f).f_h^*(\mu)} \tag{2.21}$$

In the above sections we have discussed the model of traffic related parameters that have been considered for the schemes studied and proposed in the next chapter. The values of the parameters are mentioned in chapter 4.

Chapter 3

Overlapping Coverage with Channel Restriction

3.1 Channel Restriction

Although overlapping coverage with directed retry improves the teletraffic performance, it suffers from variation in the service quality. This is because, users in some areas may have access to only one base station while others may have access to more than one. Due to this users experience different blocking probabilities depending on the location of the users. Users in non-overlapped zone experienced higher blocking probability than users in the overlapped zone. This variation can be reduced through some admission control algorithm.

To achieve fairness in the quality of service, channel restriction has been introduced [3]. We can restrict the number of available channels for new calls that are made in overlapping area to balance the blocking probabilities.

3.2 Model Description

3.2.1 Modelling Assumptions

Following assumptions have been taken for modelling directed retry and directed handoff.

- Call arrivals at the cells are Poisson.
- Blocked calls are cleared and do not return.
- There are no restrictions (other than the frequency reuse) on channels used by any mobile or any cell.
- The effects of fading and co-channel interference are not considered.

- Whenever a mobile request a channel, a channel is assigned for the duration equal to minimum of call holding time (generated from exponential distribution) and in-cell-residence time (generated from exponential distribution).
- Within a cell, calls are spread uniformly over the area of the cell.
- There is some specified probability that a call can be served by two cells simultaneously. This is calculated by fraction of coverage area that has been covered by overlapping region.
- Once a call experiences directed retry or directed handoff into an adjacent cell, it is considered to behave as if it were a call which originated in that adjacent cell. This is the approximation to the real system behaviour. However, it does not seem unrealistic in that a call which has been handed to an adjacent cell is near a cell boundary, and is likely to cross that boundary soon and so become physically located in that adjacent cell.

3.2.2 Overlapping Area

We consider a cellular system with omnidirectional base stations. These base stations are organised in a hexagonal pattern. The 'cell' for a BS is defined as the area where the received signal power from that BS is the strongest. Under the uniform propagation and flat terrain conditions, this corresponds to a hexagon for each base and every base is located at the centre of its own cell.

Fig 3.1 shows a base BS 'A' surrounded by six neighbour stations 'B-G' and their corresponding cells. The coverage area of a base is the area that is in the communication range of that base. This area is bounded by a circle and the base is also located at the centre of this circle. The coverage radius R is defined as the distance from a base to its coverage boundary. Owing to overlapping coverage, a new call may have access to two, three, or even more base stations depending on the ratio of the coverage radius to the cell radius (R/r). Here overlapping coverage upto a maximum of three base stations is considered. This corresponds to the case that the ratio R/r is between 1 and 1.5. Within this range there are three kinds of region in which a new call

can arise. In these regions a call can access one, two, or three base stations. The regions are denoted by A_1, A_2, and A_3, respectively.

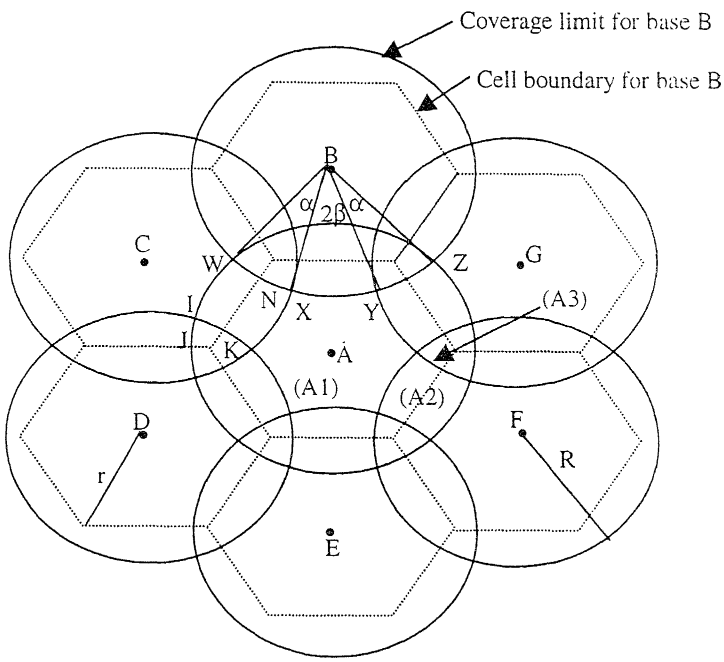


Fig 3.1 System layout for overlapping coverage

From simple geometric considerations, referring to fig 3.1 we can calculate the areas of regions A_1, A_2, and A_3 denoted by S_{A1}, S_{A2}, and S_{A3} respectively:

$$S_{A1} = \pi R^2 - 6\,S_{A2} - 6\,S_{A3} \tag{3.1}$$

$$S_{A2} = (\pi - 4\alpha - 4\beta)R^2 + 2\sqrt{3}[\sin(\alpha + \beta)]rR - \frac{3}{2}\sqrt{3}r^2 \tag{3.2}$$

$$S_{A3} = (3(\alpha + \beta) - \pi/2)R^2 - \frac{3}{2}\sqrt{3}[\sin(\alpha + \beta)]rR + \frac{3}{4}\sqrt{3}r^2 \tag{3.3}$$

For simplification, but without loss of generality, we consider only A_1 and A_2 zones. The A_3 zone is split into three A_2 zones. The area of each A_2 zone considered is :

$$S'_{A2} = S_{A2} + S_{A3}$$

From (3.2) and (3.3)

$$S'_{A2} = (-(\alpha + \beta) + \pi/2)R^2 + \frac{1}{2}\sqrt{3}[\sin(\alpha + \beta)]rR - \frac{3}{4}\sqrt{3}r^2 \tag{3.4}$$

3.2.3 Worst case CIR

CIR (Co-channel interference ratio) is defined as ratio of the desired signal power to the interference signal power due to the CCI (Co-channel interference). With overlapping coverage, a base serves some calls from neighbouring cells in addition to the calls that arise in its own cell. For those calls from neighbouring cells, the signal quality may be worse compared with those from the base's own cell, since they are more distant from the base. Worst case CIR is used to quantify the loss of signal quality due to CCI. The worst case CIR is taken at the coverage boundary and is calculated using the path loss exponent of the received power. The path loss is inversely proportional to the distance raised to an exponent η.

Table 3.1: Worst case CIR (dB) for various cluster sizes N and coverage radii R

N	i	j	R=1.0	R=1.1	R=1.2	R=1.3	R=1.4	R=1.5
4	2	0	12.29	10.30	8.40	6.58	4.80	3.05
7	2	1	17.82	15.99	14.27	12.66	11.14	9.67
9	3	0	20.20	18.40	16.74	15.18	13.71	12.32
12	2	2	22.86	21.10	19.48	17.96	16.54	15.20
13	3	1	23.59	21.84	20.23	18.72	17.31	15.98
16	4	0	25.48	23.75	22.15	20.67	19.28	17.98
19	3	2	27.03	25.31	23.73	22.26	20.89	19.60
21	4	1	27.93	26.21	24.64	23.18	21.82	20.54

Table 3.1 shows the worst case CIR in decibels for various cluster sizes N and coverage radii R with $\eta = 4$. i and j are the shift parameters for determining the locations of co-channel bases. The cluster size N and these shift parameters for hexagonal cell structure are related by:

$$N = i^2 + i.j + j^2$$

When R is extended from 1 to 1.1, the worst case CIR degrades less than 2dB for all cases in the table. Moreover, since the cluster size is discrete, usually the worst case CIR in a system without using overlapping coverage is more than the required value.

This extra CIR can be used in exchange for the improvement of the performance while the system still satisfies the requirement of signal quality.

3.2.4 Call Duration and Dwell Time

The unencumbered call duration T_c is a random variable with a negative exponential density function with mean $\overline{T_c}$ ($= \mu^{-1}$).

The dwell time can be used to model shadow-fading effects. When a user experiences a shadow fade, it is considered to leave the coverage of the base and require a hand-off, even before reaching the coverage boundary. However in microcellular systems, shadow fading is less of a problem and most hand-off needs would arise close to the coverage boundary. Dwell time is assumed to be a random variable with a negative exponential distribution of mean $\overline{T_d}$ ($= \gamma^{-1}$). The mean dwell time is taken to be proportional to the coverage radius R. Parameter γ can be approximated by the following equation [3]:

$$\gamma = V \frac{L}{\pi S} \tag{3.5}$$

where V= mean mobile speed,

L= length of the border of cell,

S= cell area

3.3 Call and Hand-off Admission Control

3.3.1 Arrival Statistics

Call arrivals at the cell is assumed to be Poisson with rate λ. Under uniform user density across the cell probability that $p_1(p_2)$ that a given call occurs in $A_1(A_2)$ zone is given by:

$$p_1 = S_{A1} / \frac{3}{2}\sqrt{3} r^2$$

$$\text{and} \quad p_2 = 1 - p_1 \tag{3.6}$$

The arrival rates of calls from A_1, and A_2 are $p_1.\lambda$, and $p_2.\lambda$.

With directed retry, calls from A_2 zones can be transferred to the neighbouring cell. The traffic flows in a cell include the following rates:

- $p_1.\lambda$: rate of new calls from A_1 zones
- $p_2.\lambda$: rate of new calls from A_2 zones
- λ_o : rate of overflow calls that were not served by their normal serving cells
- λ_h : rate of hand-off calls

3.3.2 Channel Structure

Let t be the number of channels per cell. The admission control of arrival flow is as follows.

- c channels are available for A_2 new calls and overflow calls.
- c + r channels are available for A_1 new calls.
- c + r + g channels may be used for hand-off.

We have t = c + r + g channels. The g channels are guard channels to give priority to hand-off calls. The same principle is extended to new calls. As calls in A_2 channels are favoured due to directed retry, the number of accessible channels is reduced by r channels. We refer to them as restricted channels.

We introduce the following notation for one cell:

(1) P_{b1} : Blocking probability for new calls on A_1 zone.

(2) P_{b2} : Blocking probability for new calls on A_2 zone

(3) P_{bo} : Blocking probability for overflow calls.

(4) P_{hf} : Blocking probability for hand-off calls.

Fig 3.2 depicts how the calls are handled by the system. For A_1 calls, P_{b1} is the probability that the call attempt fails. For A_2 calls, the failure probability is given by:

$$P_{f2} = P_{b2}.P_{bo} \tag{3.7}$$

Mean call failure probability for users in the whole cell is given by:

$$P_{fm} = p_1 P_{b1} + p_2 P_{b2} P_{bo} \tag{3.8}$$

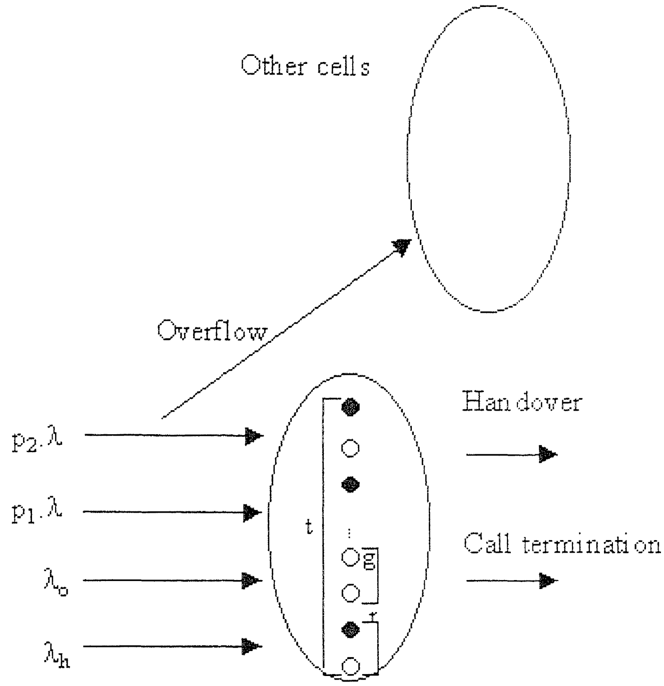


Fig 3.2 Admission control of traffic depicting normal, restricted and guard channels

3.4 Overflow and Hand-off Call

The new call arrival rate is assumed to be a Poisson process. But calls that overflow to a neighbouring cell clearly generate a non-Poisson process because arrivals happen only when channels of the originating cell are busy. The corresponding flow can be modelled by a (MMPP) Markov-modulated Poisson process [10].

Since part of the arrival flow is not Poisson and hand-off request can be generated by every call irrespective of location and type of the call, the hand-off request do not follow a Poisson process. However, as the overflow rate is small compared to the Poisson arrival rates and as the system is dimensioned to have low blocking probabilities, the hand-off flow is approximated by a Poisson process.

3.5 Analysis with The Poisson Approximation

In order to have a approximated solution, all flows at the base station is assumed to be Poisson process. A new call generated in an A_2 zone is blocked with probability P_{b2}. This call overflows to one of the six neighbouring cells. The overflow that arrives in a cell is generated by six neighbours. This is given by:

$$\lambda_o = P_{b2}.p_2.\lambda \tag{3.9}$$

With the Poisson approximation, the overflow rate has the same blocking probability as new calls from A_2 zones because both have the access to the same number of channels.

$$P_{bo} = P_{b2} \tag{3.10}$$

All users generate the hand-off arrival rate that crosses the boundary of the coverage area of the cell during the call. Flow equilibrium equation can be written as:

$$\lambda_h = P_h\,[(1 - P_{b1})\,p_1\lambda + (1 - P_{b2})\,p_2\lambda + (1 - P_{bo})\lambda_o + (1 - P_{hf})\lambda_h] \tag{3.11}$$

Where P_h is the probability that the non-blocked new or hand-off call require at least one hand-off during their session. From (2.12) and (2.17) P_h is given by:

$$P_h = \frac{\gamma}{\gamma + \mu} \tag{3.12}$$

(3.11) may be simplified as:

$$\lambda_h = P_h\,[(1 - P_{b1})\,p_1\lambda + (1 - P_{b2})\,p_2\lambda\,(1 + P_{b2}) + (1 - P_{hf})\lambda_h] \tag{3.13}$$

The hand-off arrival rate is function of the blocking probabilities, which itself are the functions of the rates λ and λ_h. This is a nonlinear equation that can be solved by the iteration.

The cell behaviour is represented by the one-dimensional Markov process whose state is defined as the number of busy channels in the cell. The infinitesimal generator is given by:

$$\overline{Q_U} = \begin{pmatrix} -\lambda_t & \lambda_t & & & & & & & \\ \mu_s & -\lambda_t - \mu_s & \lambda_t & & & & & & \\ & & \cdots\cdots & & & & & & \\ & & & c\mu_s & -\lambda_1 - c\mu_s & \lambda_1 & & & \\ & & & & & \cdots\cdots & & & \\ & & & & & (c+r)\mu_s & -\lambda_h - (c+r)\mu_s & \lambda_h & \\ & & & & & & & ,\cdots\cdots & \\ & & & & & & & -t\mu_s & -t\mu_s \end{pmatrix}$$

Where $\lambda_t = \lambda + \lambda_o + \lambda_h$ and $\lambda_1 = p_1\lambda + \lambda_h$

The Markov chain will result into the following blocking probabilities:

$$P_{b2} = \frac{\sum_{i=0}^{r-1} \rho_t^c \frac{(\rho_1 + \rho_h)^i}{(c+i)!} + \sum_{i=0}^{g} \rho_t^c \frac{(\rho_1 + \rho_h)^r}{(c+r+i)} \rho_h^i}{\sum_{i=0}^{c-1} \frac{\rho_t^i}{i!} + \sum_{i=0}^{r-1} \rho_t^c \frac{(\rho_1 + \rho_h)^i}{(c+i)!} + \sum_{i=0}^{g} \rho_t^c \frac{(\rho_1 + \rho_h)^r}{(c+r+i)} \rho_h^i} \tag{3.14}$$

$$P_{bo} = \frac{\sum_{i=0}^{g} \rho_t^c \frac{(\rho_1 + \rho_h)^r}{(c+r+i)} \rho_h^i}{\sum_{i=0}^{c-1} \frac{\rho_t^i}{i!} + \sum_{i=0}^{r-1} \rho_t^c \frac{(\rho_1 + \rho_h)^i}{(c+i)!} + \sum_{i=0}^{g} \rho_t^c \frac{(\rho_1 + \rho_h)^r}{(c+r+i)} \rho_h^i} \tag{3.15}$$

$$P_{hf} = \frac{\rho_t^c \frac{(\rho_1 + \rho_h)^r}{(c+r+g)!} \rho_h^g}{\sum_{i=0}^{c-1} \frac{\rho_t^i}{i!} + \sum_{i=0}^{r-1} \rho_t^c \frac{(\rho_1 + \rho_h)^i}{(c+i)!} + \sum_{i=0}^{g} \rho_t^c \frac{(\rho_1 + \rho_h)^r}{(c+r+i)} \rho_h^i} \tag{3.16}$$

Where $\rho_t = \lambda_t / \mu_s$, $\rho_1 = p_1\lambda / \mu_s$, and $\rho_h = \lambda_h / \mu_s$.

$1/\mu_s$ is the mean channel holding time that can be given by $1/(\mu + \gamma)$.

All the above equations can be solved by iteration in (3.13) till λ_h converges.

3.6 Analysis with MMPP

As has been discussed in section 3.4, the overflow process more precisely, does not follow a Poisson distribution. If the other arrival rates are assumed to be Poisson, the overflow can be modelled by an MMPP (Markov Modulated Poisson Process) [10]. Here the MMPP that represents the overflow of a loss multiserver system may be approximated by an IPP (Interrupted Poisson Process) [10]. An IPP is defined as an MMPP with only two states, where the instantaneous rate of the associated Poisson process in one of the states is null. The approximation has been proposed in [12] and the approach is to match the first three noncentral moments of the instantaneous arrival of the MMPP and an appropriately defined time constant. The time constant is calculated with the covariance of the instantaneous arrival rate.

In the present model, overflow arrival rate is combination of the overflows from the six neighbouring cells. At a time there may be some cells, which are generating overflows, while others are not. With the IPP approximation, each overflow is modeled as IPP defined by the following matrix:

$$Q'=\begin{pmatrix} -a & a \\ b & -b \end{pmatrix} \qquad \text{and} \qquad \Lambda'=\begin{pmatrix} 0 & 0 \\ 0 & p_2\lambda/6 \end{pmatrix}$$

where Q' is the transition matrix. Consider the overflow from one of the surrounding cells. Let state 0 is defined as the state in which there is no overflow from that cell, while state 1 denote the state in which there is overflow from that cell. 'a' and 'b' in the matrix Q'denote the rates of the exiting states 0 and 1 respectively. Arrival rates in state 0 and 1 are represented by the diagonal elements of the matrix Λ'. In state 0 there is no overflow, while in state 1 there is overflow with rate $p_2\lambda$ / 6 considering uniform user distribution throughout the cell.

The combination of six IPP's gives an MMPP associated with a $(2^6, 2^6)$ matrix. As all cells are identical, the MMPP may be reduced to seven states defined by matrix Q_U. Let state i represents that there are i cells that have no less than c busy channels. Therefore the instantaneous arrival rate is $ip_2\lambda/6$.

$$Q_U = \begin{pmatrix} -6a & 6a & & & & \\ b & -5a-b & 5a & & & \\ & 2b & -4a-2b & 4a & & \\ & & \cdots & \cdots & \cdots & \\ & & & & 6b & -6b \end{pmatrix}$$

and

$$\Lambda_U = (p_2\lambda/6).\begin{pmatrix} 0 & & & & & & \\ & 1 & & & & & \\ & & 2 & & & & \\ & & & 3 & & & \\ & & & & 4 & & \\ & & & & & 5 & \\ & & & & & & 6 \end{pmatrix}$$

It has been mentioned in the earlier section that overflow will occur, when calls from A_2 zones are blocked at the initial access. Hence the rate at which cell will exit the state 0 and 1 is given by:

$a = P_{b2}.p_2.\lambda/6.$

$b = (1 - P_{b2}).p_2.\lambda/6$

Let us consider a cell with t channels. The infinitesimal generator of the process is given by the following 7(t+1)×7(t+1) matrix:

$$\overline{Q_U} = \begin{pmatrix} A_0 & \Lambda_T & & & & & & & \\ \mu_s I & A_1 & \Lambda_T & & & & & & \\ & & \cdots & & & & & & \\ & & c\mu_s I & B_0 & \lambda_1 I & & & & \\ & & & & \cdots & & & & \\ & & & & (c+r)\mu_s I & C_o & \lambda_h I & & \\ & & & & & & \cdots & & \\ & & & & & & -t\mu_s I & Q_U - t\mu_s I \end{pmatrix} \qquad (3.17)$$

where $\Lambda_T = \Lambda_U + (\lambda + \lambda_h)I$

$\lambda_1 = p_1\lambda + \lambda_h$

$$A_i = Q_U - \Lambda_T - i\mu_s I$$
$$B_i = Q_U - \lambda_1 . I - (c+i)\mu_s I$$
$$C_i = Q_U - \lambda_h . I - (c+r+i)\mu_s I$$

The equilibrium of the Markov chain may be solved by the calculation of the stationary vector $\prod$. The system to solve is:

$$\Pi . \overline{Q_U} = 0 \tag{3.18}$$

and $\Pi . e = 1$ (3.19)

where $e^t = (1,1,1,.......1)$

The stationary vector $\prod$ consists of (t+1) vectors, each of dimension 7.

$\Pi = (\pi^0, \pi^1, \pi^2, ..., \pi^t)$, where t = c + r + g.

$$\pi^i = (\pi_0^i, \pi_1^i, \pi_2^i, ..., \pi_6^i)$$

π_j^i denote the probability that there are i busy channels in the cell, when there are overflow from j surrounding cells.

Equation (3.17) gives the (t + 1) sets of equations:

$$\pi^0(Q_U - \Lambda_T) + \pi^1\mu_s = 0$$

$$\pi^{i-1}\Lambda_T + \pi^i A_i + \pi^{i+1}(i+1)\mu_s = 0, \qquad for \quad 0 < i < c$$

$$\pi^{c-1}\Lambda_T + \pi^c B_0 + \pi^{c+1}(c+1)\mu_s = 0$$

$$\pi^{i-1}\lambda_1 + \pi^i(Q_U - \lambda_1 I - i\mu_s) + \pi^{i+1}(i+1)\mu_s = 0, \qquad for \quad c < i < (c+r)$$

$$\pi^{c+r-1}\lambda_1 + \pi^{c+r}C_0 + \pi^{c+r+1}(c+r+1)\mu_s = 0$$

$$\pi^{i-1}\lambda_h + \pi^i(Q_U - \lambda_h I - i\mu_s I) + \pi^{i+1}(i+1)\mu_s = 0, \qquad for \quad c+r < i < c+r+g$$

$$\pi^{t-1}\lambda \;\; + \pi^t(Q_U - t\mu_s I) = 0.$$

These equations may be solved by a Gauss-Seidel iteration.

The blocking probabilities P_{b1}, P_{b2}, P_{bo}, and P_{hf} are given by:

$$P_{bo} = \frac{\sum_{k=c}^{c+r+g} \sum_{i=0}^{6} i\pi_i^k}{\sum_{k=0}^{c+r+g} \sum_{i=0}^{6} i\pi_i^k} \tag{3.20}$$

$$P_{b1} = \sum_{k=c+r}^{c+r+g} \sum_{i=0}^{6} \pi_i^k \tag{3.21}$$

$$P_{b2} = \sum_{c}^{c+r+g} \sum_{i=0}^{6} \pi_i^k \tag{3.22}$$

$$P_{hf} = \sum_{i=0}^{6} \pi_i^{c+r+g} \tag{3.23}$$

We can calculate all the blocking probabilities assuming λ_h and the characteristic of IPP process are known. An iteration is applied on flow conservation equation (3.11) and the blocking probability calculation till λ_h converges.

3.7 Channel Rearrangement

When overlapping coverage exists in a system, it is not likely that users in all areas can establish an acceptable quality link with several bases. Users in some areas may have access to only one base while others can have access to more than one. From the earlier discussion, it has been cleared that calls having access to more than one base station may experience low blocking probability than the calls having access to only one base station, owing to higher channel usage that is possible.

To let these calls (calls from A_1 zone) benefit from overlapping coverage, channel rearrangement can be used. Channel rearrangement allows an ongoing call in an overlapped area to continue service through an alternative base station This can free a channel for use by a new or hand-off call that has access to only one base. If rearrangements are used, it is not always necessary to block a call which originates in a nonoverlapping region and finds no channel available at the only target base. Channel rearrangement can also be used to accommodate a hand-off call that enters a nonoverlapping region and finds all channels occupied at the only target base.

Since overlapping coverage schemes help to accommodate calls that are more distant from the base, the teletraffic performance improvements are at the expense of more users having lower signal quality.

3.7.1 State Characterisation

For channel rearrangement to be possible there must be at least one ongoing call in an overlapping region. Single variable state representation cannot provide this information. Therefore state s of a given base is now identified by two non-negative integers a(s) and b(s), where a(s) is the number of calls in service that can access only one base in state s and b(s) is the number of calls in service having access to more than one base. If for a particular state s, b(s) is greater than zero, there is a possibility of channel rearrangement to accommodate an arrival. The number of calls in service at a base in state s is given by:

$j(s) = a(s) + b(s)$

A permissible state must satisfy the constraint that the number of calls carried by a base is less than or equal to total number of channels (= t). All permissible states are labelled from $s = 0$ to $s = s_{max}$.

3.7.2 Call Arrivals

If λ and λ_h are the rate of new and handover call, arrival flow at the base station consists of the following flows:

(1) New call arrivals from A_1 zone : $p_1\lambda$

(2) New call arrivals from A_2 zone : $p_2\lambda$

(3) Hand-offs entering region A_1 : $p_{h1}\lambda_h$

(4) Hand-offs entering region A_2 : $p_{h2}\lambda_h$

(5) Overflow calls : λ_o

(6) Rearrangement arrivals : λ_r

New call arrival rates from A_1 and A_2 zones, and overflow calls are same as have been discussed in section 3.5. With rearrangement hand-off call arrival and rearrangement arrivals require some details here.

3.7.3 Hand-off Call Arrivals

Hand-off calls entering into a cell from neighbouring cell may be in overlapped region (A_1 zone) or non-overlapped region (A_2 zone). When a hand-off call arrive at the

base station, it will decide whether it is from A_1 or A_2 zone depending on the probability p_{h1} and p_{h2} respectively. The fraction of hand-offs that enter region A_1 is given by (see fig 3.1) the ratio of the length of arc XY ($2\beta R$) to the length of the border ($2\pi R$). There are six such type of hand-offs. Therefore p_{h1} and p_{h2} may be written as:

$$p_{h1} = 6\frac{2\beta R}{2\pi R} = \frac{6\beta}{\pi}$$

and $$p_{h2} = 1 - p_{h1}$$

3.7.4 Rearrangement Arrivals

A base station also takes the demands from neighbouring bases owing to channel rearrangement. Rearrangement is done to exploit the coverage region to benefit the user from A_1 zone. The specific algorithm that has been tested for new calls from A_1 zone is as follows:

1. Whenever a new call from A_2 zone is blocked, use directed retry as discussed earlier.
2. Whenever a new call from A_1 zone is blocked at the initial access, check whether the number of busy channels is greater than or equal to (c + r).
3. If number of busy channels is greater than (c + r), call will be blocked.
4. Else if number of busy channels is equal to (c + r), check the number of busy channels (b(s)) from A_2 zones.
5. If b(s) is greater than zero, then rearrangement of calls will be attempted, otherwise call will be blocked.
6. Choose the ongoing call from A_2 zones having least signal power.for transfer to neighbouring base. The motivation here is that the call with the least signal power is most likely to be near the coverage boundary and likely to need a hand-off. This approach will not only fulfil the requirement of channel rearrangement, but also will least degrade the signal quality for those chosen calls.
7. Selected call will be transferred to the neighbouring base station. Check for the number of bu :y channels in the neighbouring cell.
8. If this is greater than or equal to c, call will be blocked, otherwise it will be assigned a channel.

Channel rearrangements for new calls may occur when base is in state s such that j(s) = c + r and b(s) > 0. The probability of this kind of states is denoted by δ_1, which can be given as:

$$\delta_1 = \Pr\{s : j(s) = c + r \quad and \quad b(s) > 0\} \tag{3.24}$$

This is the probability that new call originating in region A_1 may result in a channel rearrangement. It follows that the rearrangement arrival due to new call arrivals in region A_1 of a neighbouring base is:

$$\lambda_{rn} = 6\delta_1 \lambda p_1 \tag{3.25}$$

Similarly, the rearrangement arrival rate for accommodating hand-off calls at neighbouring bases can be derived. Rearrangement is done at the state s such that j(s)= t and b(s) > 0. This probability is denoted by δ_2.

$$\delta_2 = \Pr\{s : j(s) = t \quad and \quad b(s) > 0\} \tag{3.26}$$

A base can serve the rearrangement arrival which is used for accommodating a hand-off call under the states such that j(s) < t. Therefore rearrangement arrival rate due to hand-off call is given by:

$$\lambda_{rh} = 6\delta_2 \lambda_h p_{h1} \tag{3.27}$$

3.7.5 Call Completions

The call completion rate is exponentially distributed with parameter μ_c, where $1/\mu_c$ is the average call duration time. When cell is in state s, call completion rate is given by $s\mu_c$.

3.7.6 Hand-off Departures

A hand-off departures occur only when the communicating user completes the dwell time T_d, which is a random variable having exponential distribution having mean $1 / \gamma$. In state s hand-off departure rate is given by $s\gamma$.

3.7.7 Rearrangement Departures

There are two kinds of rearrangement departures: one for accommodating new calls that arise in region A_1 and the other for accommodating hand-off arrivals that enter region A_1.

First consider a rearrangement departure which accommodates a new call. Conditions for this is described in section 3.7.4. For a successful rearrangement alternate BS must be able to accommodate the call that is chosen to be transferred. The chosen call is not given priority because this rearrangement can only be used for accommodating a new call. Hence probability of this event is equal to the probability of blocking for new call arrivals from A_2 zones. This is given by P_{b2}. The success probability is $(1- P_{b2})$. Therefore, rearrangement departure rate for new calls can be written as:

$$\mu_{dn} = \lambda p_1 (1 - P_{b2}) \tag{3.28}$$

Following a similar development as for accommodating a new call, the rearrangement departure rate for accommodating a hand-off call can be obtained. This is given by:

$$\mu_{dh} = \lambda_h p_{h1} (1 - P_{hf2}) \tag{3.29}$$

where P_{hf2} is failure probability for hand-offs entering region A_2.

3.8 Performance Measures

3.8.1 Blocking Probabilities

We consider the following blocking probabilities in the system.

- P_{b1} : Blocking probability for new call on A_1 zone.
- P_{b2} : Blocking probability for new call on A_2 zone.
- P_{bo} : Blocking probability for overflow call to the neighbouring cell.
- P_{hf1} : Blocking probability for hand-off call entering region A_1.
- P_{hf2} : Blocking probability for hand-off call entering region A_2.

With channel rearrangement, a new call which originates in region A_1 is blocked if one of the following events occurs at the time of origination.

(i) The number of calls in progress at the base is more than c + r.

(ii) The number of calls in progress at the base is equal to (c + r) but none is in the overlapping region.

(iii) The number of calls in progress at the base is equal to (c + r) and at least one is in the overlapping area, and the call that is chosen to be transferred to a neighbouring base cannot find an available channel at the target base.

The probability of the first event is denoted by χ, expressed as:

$$\chi = \Pr\{s : j(s) > c + r\} \tag{3.30}$$

The probability of second event is just the state probability P(s') in which a(s')=c + r and b(s') = 0.

For the third, the probability that there are c+r busy channels with at least one of them in the overlapping region, is just δ_1 given in (3.24). The chosen will be blocked by the target base station with probability P_{b2}. Then combining the above three events, the failure probability in region A_1 is given by:

$$P_{b1} = \chi + P(s') + \delta_1 . P_{b2} \tag{3.31}$$

Failure probability for calls on A_2 zones is given by:

$$P_{f2} = P_{b2} . P_{bo} \tag{3.32}$$

Mean failure probability for new calls in the system is given by:

$$P_{fm} = p_1 . P_{b1} + p_2 . P_{f2} \tag{3.33}$$

3.8.2 Forced Termination Probability

One must distinguish between hand-off arrivals and rearrangement arrivals. Hand-off arrivals result from a communicating user entering the coverage area of the given BS and leaving the coverage area of a BS. Rearrangement arrivals, on the other hand, result from the need of an adjacent base to accommodate a call in its non-overlapping area. With channel rearrangement mean hand-off failure probability P_{hf} is given by the weighted sum of P_{hf1} and P_{hf2}.

$$P_{hf} = p_{h1} . P_{hf1} + p_{h2} . P_{hf2} . P_{hf2} \tag{3.34}$$

Hand-offs that enter region A_1 of a target base fail if one of the events E_1 or E_2 occurs $\{E_1\}$ is the event that all channels are occupied and none of the calls is in the overlapping region. Probability of this event is:

$$P(s') = \Pr\{s' : j(s') = t \quad and \quad b(s') = 0\} \tag{3.35}$$

$\{E_2\}$ is the intersection of events E_{2a} and E_{2b}. $\{E_{2a}\}$ is the event that all channels are occupied with at least one of the calls in the overlapping region. $\{E_{2b}\}$ is the event that the chosen call for transfer to the neighbouring base find no channels. $P\{E_{2a}\}$ is just δ_2 given (3.26). $P\{E_{2b}\}$ is equal to P_{hf2}. Hence P_{hf1} can be written as:

$$P_{hf1} = P(s') + \delta_2 . P_{hf2} \tag{3.36}$$

From (3.34) and (3.35) mean hand-off failure probability can be calculated.

The probability of forced termination given that the call has been accepted is:

$$P_{FT} = \frac{p.P_{hf}}{(1 - p(1 - P_{hf}))} \tag{3.37}$$

where p is the probability that a call requires at least one hand-off before boundary crossing.

3.8.3 Hand-off Activity

Hand-off activity is the expected number of hand-offs that a non-blocked call will experience. From (2.20) this is given by:

$$\overline{H} = \frac{(1 - P_{fm})\gamma}{\mu + \gamma P_{hf}} \tag{3.38}$$

3.8.4 Carried Traffic

The carried traffic A_c per base station is the average number of channels that are occupied. This is given by:

$$A_c = \sum_{s=0}^{s_{max}} j(s).p(s) \tag{3.39}$$

3.9 Rearrangement Probability

Since both new calls and hand-off calls result in channel rearrangement, two rearrangement probabilities are considered as additional performance measures. One is the probability that a new call generates a rearrangement, denoted by P_{rn}. The other is the probability that a hand-off call generates a rearrangement, denoted by P_{rh}.

The probability P_{rn} is the average fraction of new calls that cause channel rearrangements. For a new call to induce channel rearrangement, following three conditions must be satisfied:

(a) The new call must arise in a nonoverlapping region.

(b) The corresponding base station must be in some state for which $j(s) = c + r$ and $b(s) > 0$.

(c) A channel must be available to serve the rearranged call.

The probability of the first event is just the fraction of area that has access to one base. This has been developed as p_1. The probabilities of the second and third event are given by δ_1 and $(1 - P_{b2})$ respectively. It follows that:

$$P_{rn} = p_1 \delta_1 (1 - P_{b2}) \tag{3.40}$$

Similarly, the probability P_{rh} is the average fraction of hand-offs that cause channel rearrangements. Three conditions must be satisfied for rearrangement to be caused by hand-off call.

(a) The hand-off must enter a non-overlapping region. Probability of this has been developed as p_{h1}.

(b) The corresponding base station must be in some state for which all channels are fully occupied and at least one of the served calls is in an overlapping region. Probability of this has been developed as δ_2 in (3.26).

(c) Channel must be available to serve the rearranged call. Probability for this is given by $(1 - P_{hf2})$.

The rearrangement probability of hand-offs can be calculated by:

$$P_{rh} = p_{h1} \delta_2 \left(1 - P_{hf2}\right) \tag{3.41}$$

3.10 Concluding Remarks

In the above sections, we have presented the analytical framework for the analysis of the performance of the microcellular systems with restriction. Two approaches have been discussed. One with Poisson approximation for overflow arrivals and other with IPP model for overflow arrivals. Specific algorithm for channel rearrangement that has been tested in this thesis is also presented.

Chapter 4

Results and Performance Analysis

In this chapter, we present the results obtained by simulation and performance analysis of the microcellular system with the following schemes:

(1) Directed retry without restriction (Case 1).

(2) Directed retry with restriction (Case 2).

(3) Channel rearrangement or directed hand-off with restriction (Case 3).

4.1 Simulation Model

The system that is used for simulation is a homogeneous 49-cell system with 7-cell reuse groups. The region of interest is represented as shown in the fig 5.1, with a wraparound structure. This means whenever a mobile crosses the region boundaries, it is considered to be entering another cell of the opposite side. For example, when a mobile crosses the boundary from cell #1, it may enter one of the cells #7, #14, #43 or #44. This is applicable for all boundary cells.

In this thesis, we have implemented a *Discrete-Event* simulation technique for simulating our cellular system. In this simulation technique, the system's state variables change instantaneously only at those points in time where events actually occur. At each instants of time system has the information about the next event to occur. A simulation clock keeps track of the current value of simulated time as the simulation proceeds. The simulation clock is initialised to zero, and the clock is subsequently advanced to the next immediate future event, each time the current event is processed. At this time, the state of the system is also updated to account for the fact that an event has occurred. Since all state changes occur only at event times, periods of inactivity are skipped over by jumping the clock from one event time to the next. The simulation stops when the clock reaches the pre-specified end time for the simulations or some other pre-specified termination criteria.

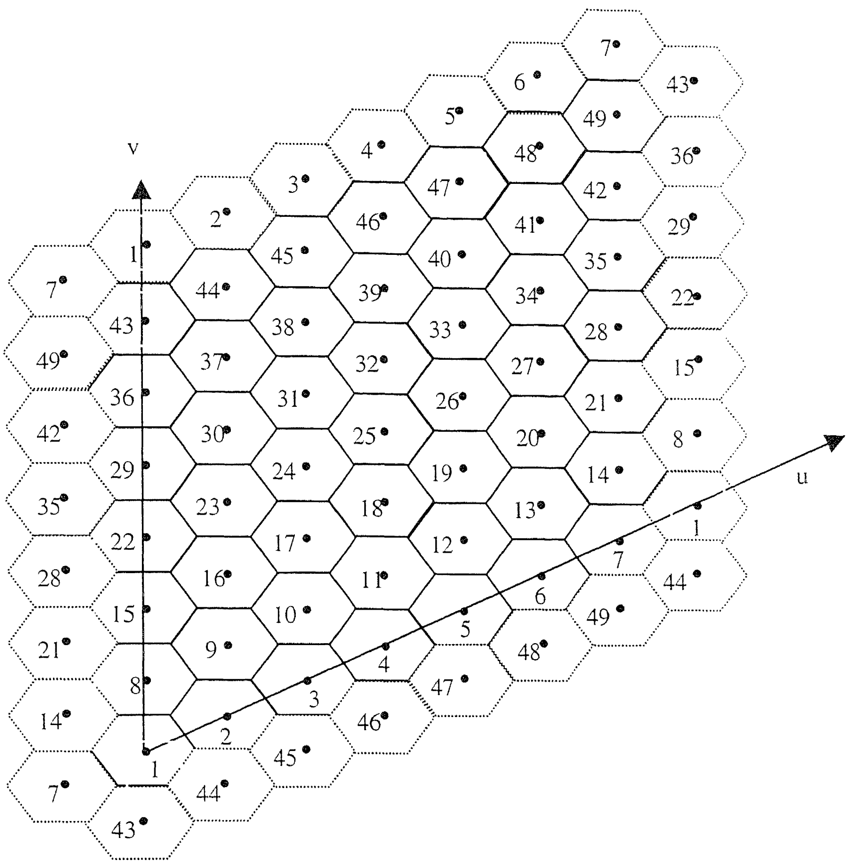


Fig 4.1 Layout For 49 cell system

4.1.1 Parameters Used in Simulation

Following considerations have been taken for the system.

(i) Number of channels per cell : t = 18.

(ii) Mean Communication duration: $T_c = 100$ s.

(iii) The ratio of coverage radius to the cell radius (R/r) is considered to be 1.15 for study. In such a configuration probability that a call will arise from A_1 or A_2 zone is calculated from (3.4) as:

$$p_1 = 0.481562 \quad \text{and} \quad p_2 = 0.518438$$

(iv) Mean dwell time of a mobile: T_d = 66.67 s. This is adjusted proportional to the coverage radius R.

(v) Two guard channels (g = 2) and two restricted channels (r = 2) were considered for the analysis of the system with restriction and with rearrangement.

4.1.2 Hand-off Arrival Rate

Hand-off arrival rate, as has been discussed in section 2.3, 2.4, and 2.5, depends on the new call arrival rate, mean failure probability for new calls, and hand-off failure probability. Failure probabilities itself dependent on the new and hand-off call arrival rates. Iterative procedure is used to calculate the hand-off call arrival rate. Iteration is used on (3.11) for our schemes, till hand-off rate converges. Table 4.1 shows the hand-off call arrival rate with different loads for the three cases.

Table 4.1 Hand-off arrival rates for different values of load on the base station

Load at the BS (Erlangs)	Hand-off Arrival rate (Case 1)	Hand-off Arrival rate (Case 2)	Hand-off Arrival rate (Case 3)
6.0	0.089991	0.089993	0.089998
6.5	0.097479	0.097484	0.097497
7.0	0.104958	0.104969	0.104987
7.5	0.112416	0.112434	0.112472
8.0	0.119697	0.119798	0.119937
9.0	0.133935	0.134018	0.134465
10.0	0.147329	0.147181	0.148162
12.0	0.169847	0.168727	0.170736
14.0	0.186958	0.183659	0.186088

4.1.3 Parameters of Interest

With the above mentioned parameters, simulations have been carried out for existing schemes (case 1 and case 2) as well as the proposed scheme (case 3). Parameters of interest are:

(a) Failure probability for new calls on A_1 zones (P_{b1}).

(b) Failure probability for new calls on A_2 zones (P_{f2}).

(c) Forced termination probability (P_{FT}).

(d) Hand-off activity

4.2 Results

In this section we will show the analytical and simulation results for case 1 and 2. Analytical results have been produced using IPP approximation for the overflow calls as discussed in chapter 3. Simulation results have been presented for case 3. Due to large computational complexity we have not calculated the confidence interval.

4.2.1 Failure Probabilities for New calls

Table 4.2 New call failure probabilities with varying load for case 1

Load (Erlangs)	P_{b1}		P_{f2}	
	Analytical	Simulation	Analytical	Simulation
6.0	0.000440	0.000376	0.000000	0.000000
6.5	0.000981	0.001001	0.000001	0.000000
7.0	0.001992	0.001817	0.000005	0.000000
7.5	0.003725	0.003306	0.000015	0.000018
8.0	0.006491	0.006305	0.000047	0.000048
9.0	0.016473	0.015860	0.000294	0.000353
10.0	0.034392	0.030336	0.001254	0.001074
12.0	0.097388	0.083893	0.009851	0.007667
14.0	0.185927	0.153862	0.036181	0.024679

Table 4.3 Failure probabilities with varying load for case 2

Load (Erlangs)	P_{b1}		P_{f2}	
	Analytical	Simulation	Analytical	Simulation
6.0	0.000279	0.000188	0.000013	0.000012
6.5	0.000622	0.000608	0.000048	0.000036
7.0	0.001265	0.001242	0.000148	0.000174
7.5	0.002369	0.002460	0.000399	0.000446
8.0	0.004136	0.004123	0.000953	0.000048
9.0	0.010554	0.009717	0.004031	0.003918
10.0	0.022227	0.021184	0.012345	0.012589
12.0	0.064823	0.057183	0.058042	0.054993
14.0	0.129332	0.099821	0.148538	0.123249

Table 4.4 Failure probabilities with varying load for case 3 (Simulation results)

Load (Erlangs)	P_{b1}	P_{f2}
6.0	0.000039	0.000012
6.5	0.000144	0.000054
7.0	0.000339	0.000176
7.5	0.000611	0.000387
8.0	0.001267	0.000894
9.0	0.004078	0.004164
10.0	0.009318	0.013437
12.0	0.034661	0.060158
14.0	0.071223	0.139491

4.2.2 Forced Termination Probability (P_{FT})

Table 4.5 Forced termination probability for three schemes

Load (Erlangs)	Case 1		Case 2		Case 3
	Analytical	Simulation	Analytical	Simulation	Simulation
6.0	0.000022	0.000022	0.000014	0.000006	0.000000
6.5	0.000057	0.000063	0.000036	0.000031	0.000000
7.0	0.000132	0.000122	0.000084	0.000084	0.000000
7.5	0.003725	0.000291	0.000177	0.000200	0.000000
8.0	0.000539	0.000538	0.000344	0.000331	0.000000
9.0	0.001664	0.001602	0.001067	0.001027	0.000000
10.0	0.004111	0.003743	0.002661	0.002453	0.000012
12.0	0.015301	0.012145	0.010236	0.008140	0.000084
14.0	0.036183	0.024767	0.025284	0.016244	0.000363

4.3 Performance Analysis

4.3.1 Failure probabilities for new calls

In this section we compare a system with restriction (case 1) with an equivalent system without restriction (case 2). The total number of channels remains unchanged. Both simulation and analytical results for failure probabilities for A_1 and A_2 zones have been provided in table 4.2-4.3 and fig 4.2-4.3. It can be seen from fig 4.2 and 4.3 that analytical and simulation results are very close to each other. It can further be seen that the failure probabilities for A_1 and A_2 zones are closer to each other for case 2. Thus system tends to provide a more fair treatment of calls arising in different zones. The slope for the A_2 calls is higher as P_{f2} is a function of square of the blocking probability.

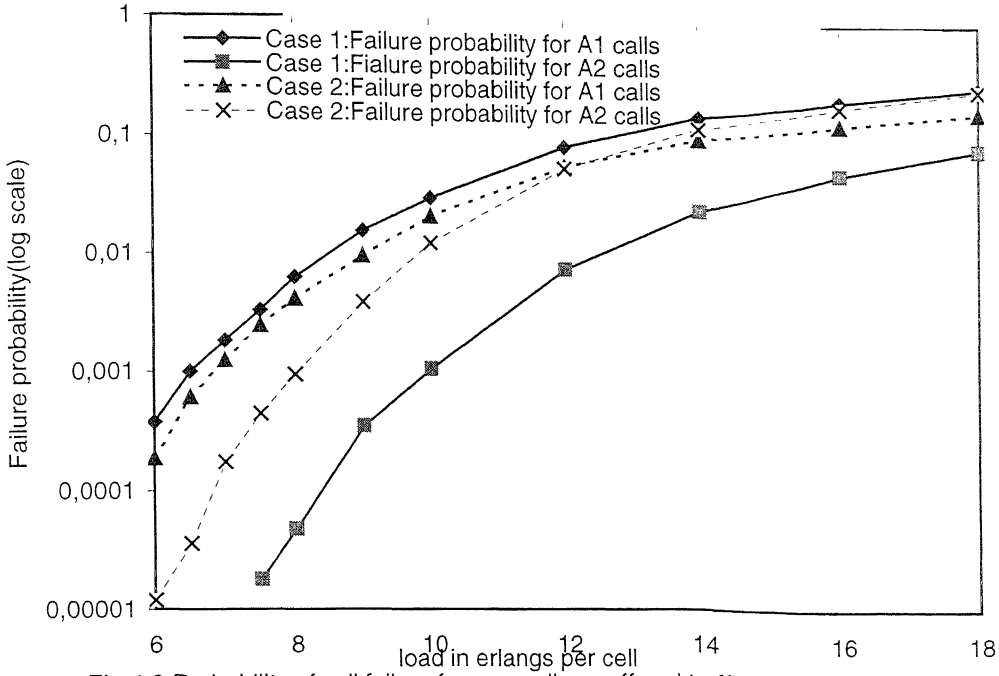


Fig 4.2 Probability of call failure for new calls vs offered traffic (load) to a cell (Simulation)

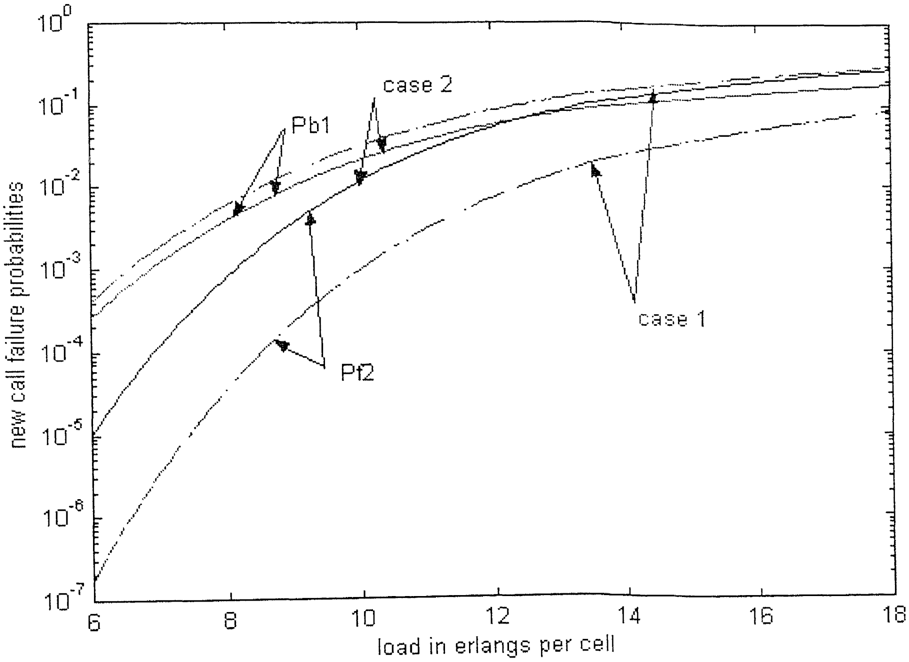


Fig 4.3 New call failure probabilities vs offered traffic (load) to a cell (Analytical)

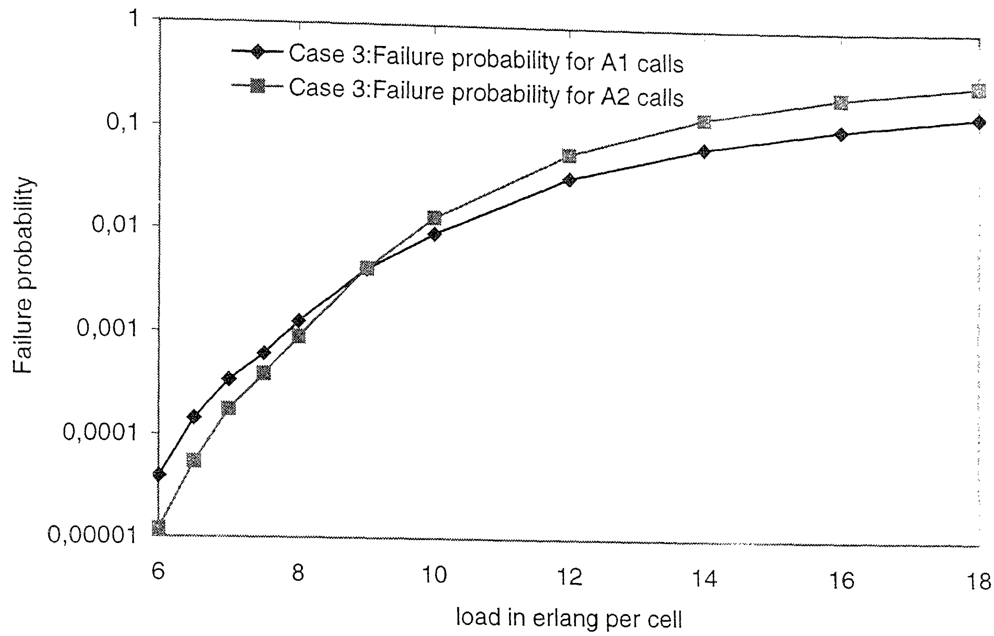


Fig 4.4 Failure probabilities vs load for case 3

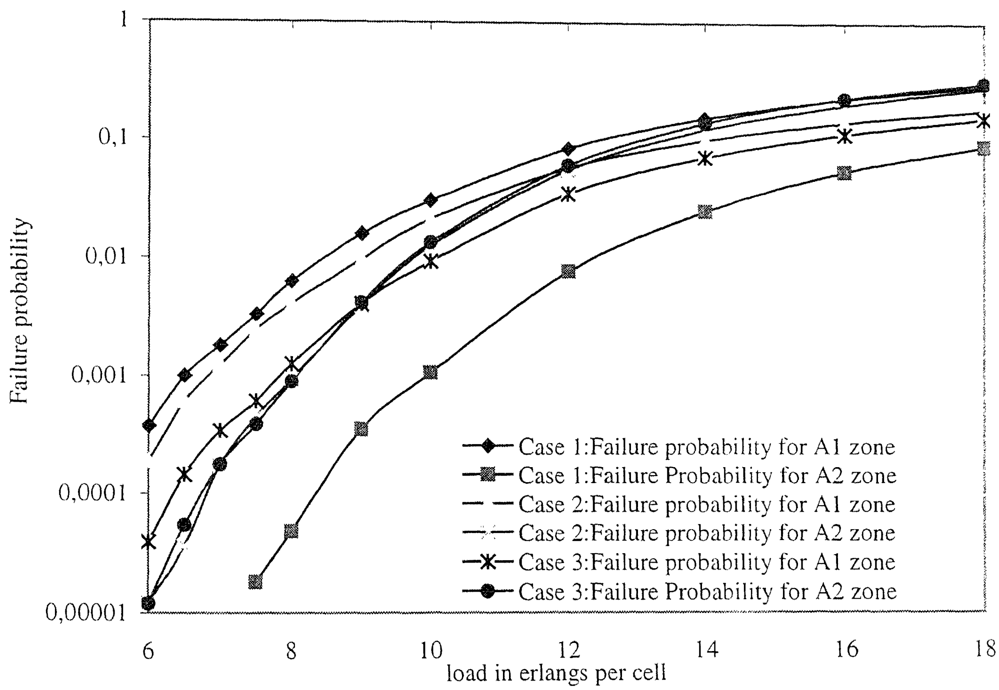


Fig 4.5 Failure probabilities vs load for three cases

As discussed in section 3.7 overlapping region can also be exploited to further decrease the failure probability for A_1 zones using channel rearrangement. Simulation results for this (case 3) is provided in table 4.4 and fig 4.4. This also provides the fair treatment to the calls arising in different zones with lower failure probability for A_1 zones than with case 2. This is illustrated in fig 4.5.

It can be seen in fig 4.5 that with rearrangement failure probability for new calls arising from A_1 zone decreases in comparison to the case 2. At the same time there is no change in failure probability for A_2 zones. Hence the system with this scheme (case 3) is better than the system without restriction (case 3).

4.3.2 Mean failure probability

Mean failure probability is the weighted sum of failure probabilities for A_1 and A_2 zones. As per the terminology of chapter 3, mean failure probability can be written as:

$$P_{fm} = p_1.P_{b1} + p_2.P_{f2}$$

Fig 4.6 shows the mean failure probability for all cases with varying loads. It can be seen that restriction and rearrangement tends to reduce the mean failure probability for low load. Above 0.1 calls per second (10 erlangs), the mean failure probability is higher with restriction (case 2). It must be stressed that the comparison is made with the same number of guard channels. It will be seen in the further sections, the number of guard channels may be reduced if restricted channels are used, and consequently, the mean failure probability. The crossing between the curves for case 1 and 2 is just for a load above the typical operating point (1% mean failure probability). In very high load conditions, restriction may be easily deactivated if favouring A_2 traffic proves to optimize the total throughput.

With rearrangement (case 3) crossing point is above 0.12 calls per second (12 erlangs). Hence system with this scheme can be used upto higher load than the system without restriction (case 2). Effect of the number of guard channels on the mean failure probability is same as case 2.

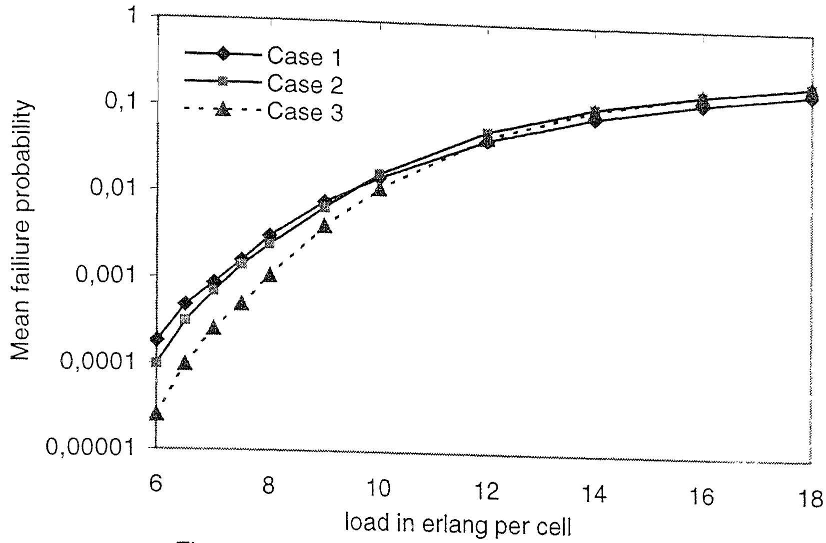


Fig 4.6 Mean failure probabilities vs load for three cases

4.3.3 Forced termination probability

Fig 4.7 shows the forced termination or call dropping probability for three cases. Increased improvement can be achieved with overlapping schemes (case 2 and 3). Channel rearrangement provides substantial improvement over other two schemes.

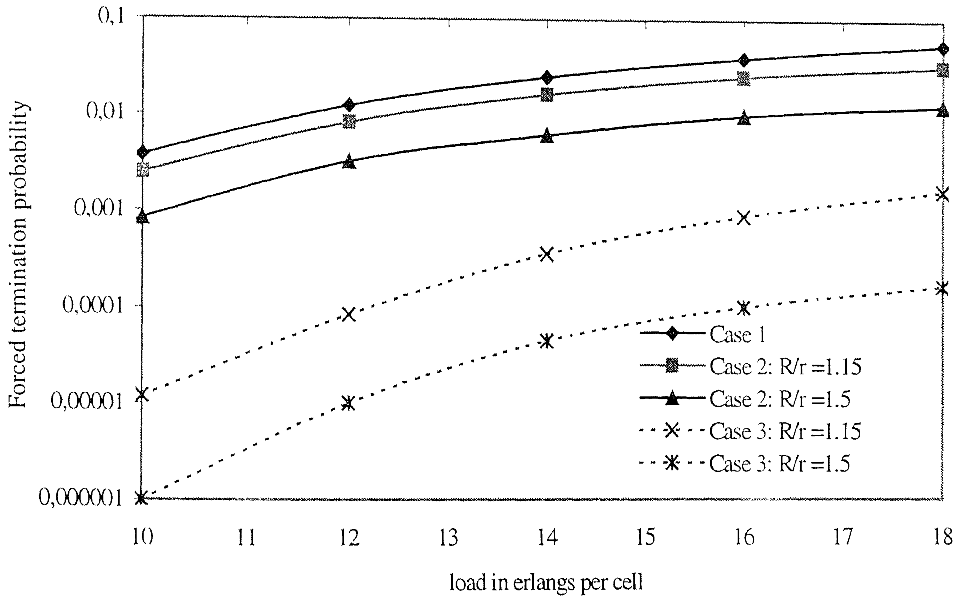
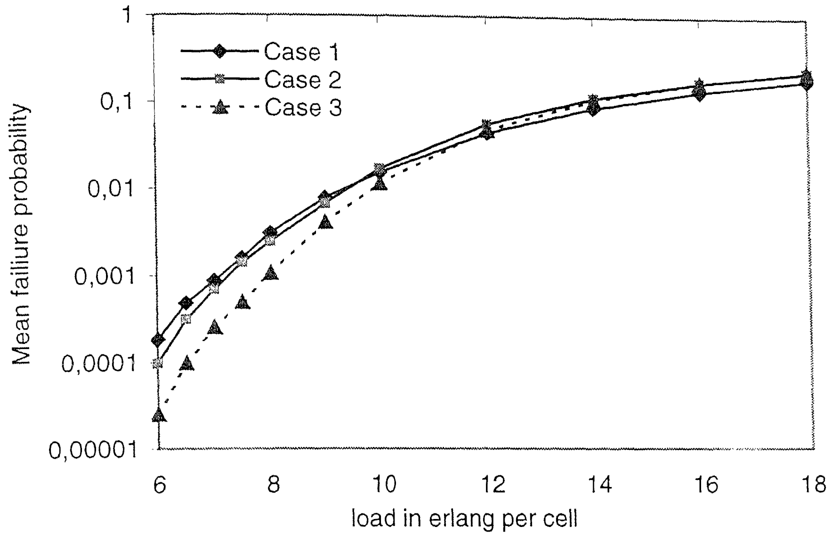


Fig 4.7 Forced termination probability vs load



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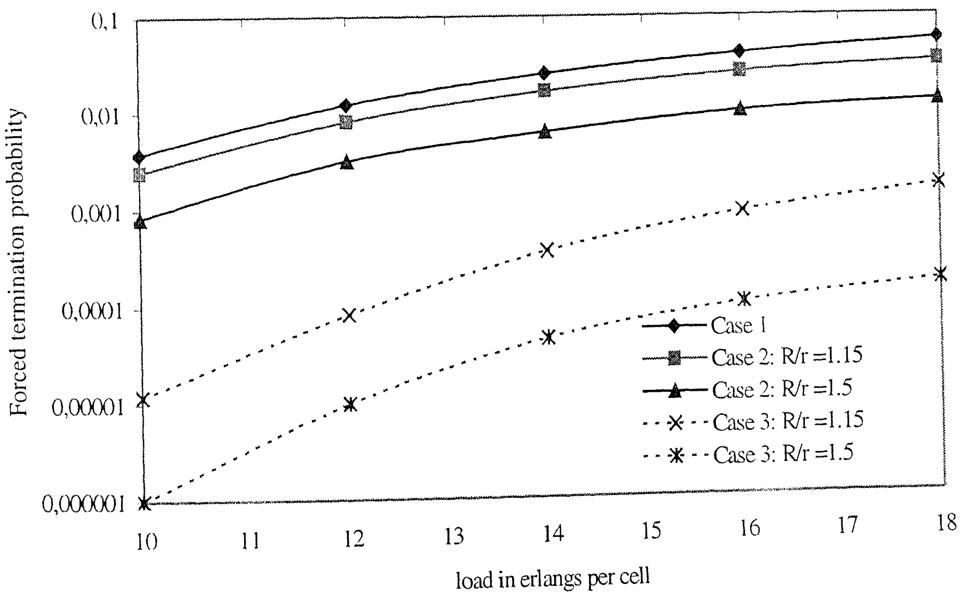

Fig 4.7 Forced termination probability vs load

Plot has also been taken for R/r equal to 1.5. It can be seen that forced termination probability decreases as ratio R/r increases for case 2 and 3. Hence as overlapping coverage area increases forced termination probability decreases.

4.3.4 Fairness Coefficient

Fairness coefficient is defined as the ratio P_{b1} / P_{f2}. Fig 4.8 shows the comparison among the three cases with fairness coefficient. It can be seen that fairness coefficient is approximately equal to one with case 2 and 3, while fairness coefficient is very large with case 1.

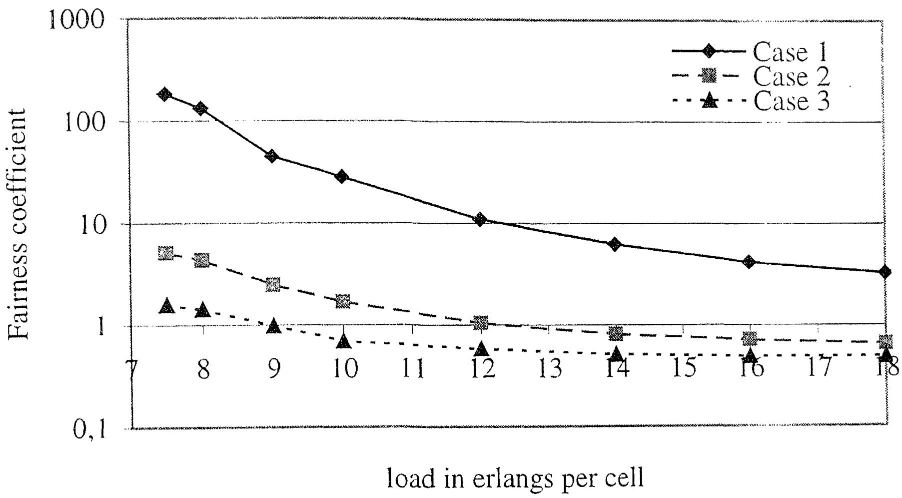

Fig 4.8 Fairness coefficient vs load

4.3.5 Mean number of hand-offs

Fig 4.9 represents the plot between mean number of hand-offs experienced by the mobile during the time engaged in conversation for three cases. Plots have also been taken for R/r equal to 1.5 for case 2 and 3. It can be seen that with larger R/r, mean number of hand-offs decreases since the time that a call resides in the coverage of a base is larger. With channel rearrangement (case 3) mean number of hand-offs is more than without it This is because it is harder for a call to be forcedly terminated than without the channel rearrangement (case 2).

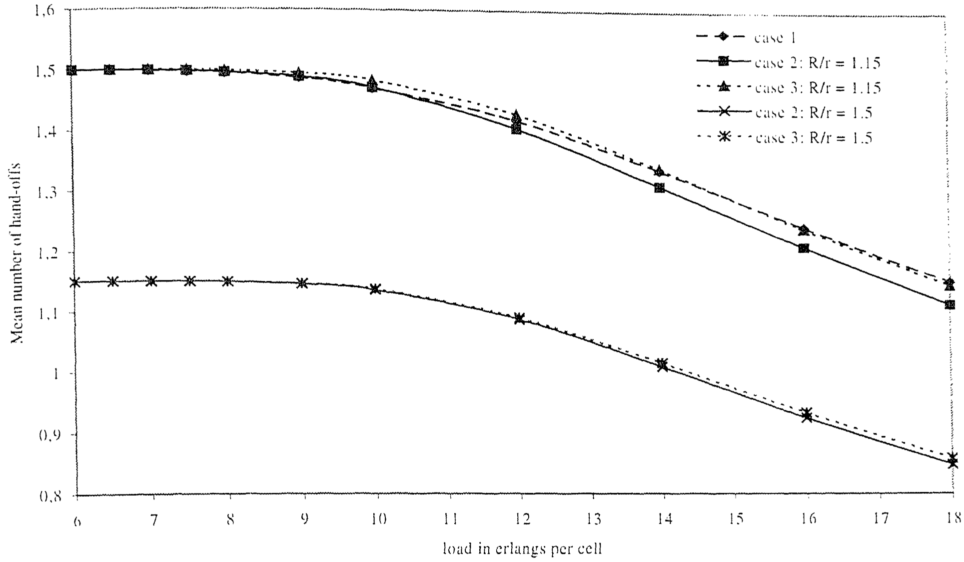

Fig 4.9 Mean number of hand-offs vs load

4.3.6 Rearrangement probability

Fig 4.10 shows the probabilities of rearrangements due to hand-offs as well as due to new calls with varying load at the BS. The probability of rearrangement due to hand-offs is less than the probability of rearrangement due to new calls. This is because hand-offs are given priority over new calls. Hence fewer rearrangements are needed to accommodate the hand-offs.

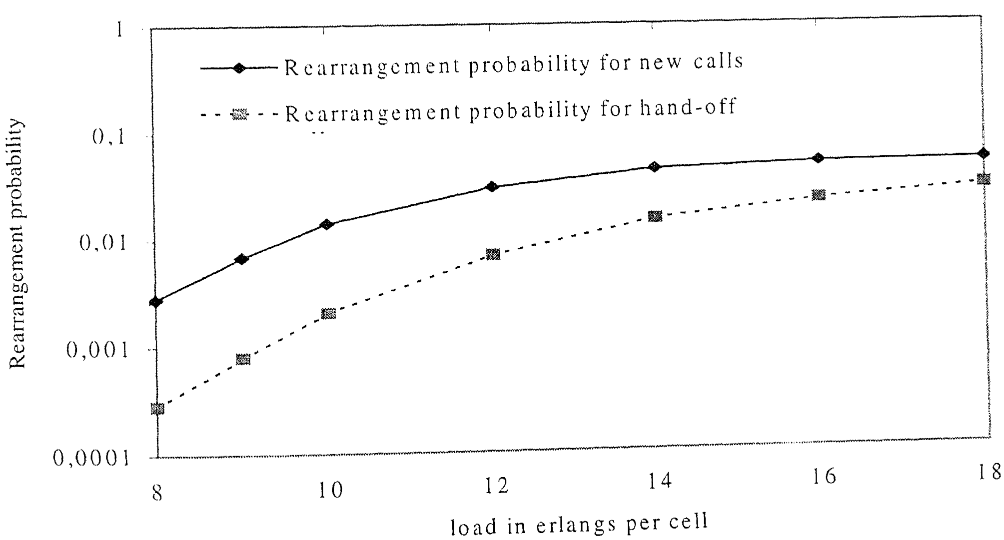

Fig 4.10 Rearrangement probability vs load

4.4 Study of the system under restriction

In this section we study the behaviour of the system for a new call arrival rate of 0.1 per second per cell (the offered load is 10 Erlangs) and a defined number of channels in each cell (t = 18), but for various configurations from zero to three guard channels and from zero to three restricted channels. Results have been listed in Table 4.6. It can be seen in the table that introduction of one restricted channel reduces the mean failure probability as well as forced termination probability regardless of the number of guard channels. As discussed in section 4.3.4, the call failure probabilities are more balanced with restricted channels. If the number of restricted channels is chosen to balance at best failure probabilities (for example two guard channels and two restricted channels), the mean call failure probability is higher than without restriction and consequently the efficiency of the system is reduced. But advantage in this case is the decreased forced termination probability (call dropping probability) and consequently quality of service is better.

Table 4.6 Failure probabilities (in percentage) with various configurations

g	r	P_{b1}	P_{f2}	P_{fm}	P_{FT}
0	0	0.67	0.00	0.33	1.01
0	1	0.55	0.03	0.28	0.81
0	2	0.45	0.15	0.30	0.70
0	3	0.37	0.50	0.44	0.55
1	0	1.72	0.02	0.83	0.64
1	1	1.35	0.15	0.73	0.52
1	2	1.03	0.49	0.75	0.41
1	3	0.92	1.32	1.13	0.30
2	0	3.22	0.10	1.60	0.38
2	1	2.49	0.40	1.41	0.31
2	2	2.06	1.25	1.64	0.24
2	3	1.68	3.14	2.44	0.20
3	0	5.28	0.30	2.70	0.21
3	1	4.42	1.12	2.71	0.17
3	2	3.53	2.70	3.14	0.13
3	3	2.83	6.26	4.60	0.09

For a defined call dropping probability of 0.31%, it can be seen from table 4.7 that minimum of three guard channels are required without restriction leading to a call failure probability of 0.027. On the other hand in a system including two restricted channels, the number of guard channels may be reduced to two and the mean call failure probability reduces to 0.0141 resulting in increased carried traffic.

Chapter 5

Conclusion

In this work, we have presented the analytical and simulation model to exploit the overlapping coverage area for performance improvement of the system. We have compared a system with restriction with an equivalent system without restriction. Performance of the system has been analysed by two methods:

(1) An approximation assuming a Poisson process for the overflow traffic resulting from directed retry.

(2) Modeling the overflow traffic by IPP (Interrupted Poisson process)

Results from both approaches match closely and follow approximately those obtained by simulation. Numerical evaluation and simulation results for a given configuration show the significant gain achieved through balancing the failure probabilities (with restriction) throughout the service area. We have observed the decrease in forced termination probability as well as in mean failure probability. We can observe further decrease in failure probability experienced by users in non-overlapping zone through channel rearrangement or directed hand-off alongwith the restriction. A substantial improvement in forced termination probability is achieved through channel rearrangement.

Future Scope

The numerical results presented in this thesis were produced considering even traffic distribution across the region, but this is not realistic. We need some model with a peak distribution in the central business area. The question here arises how quickly the traffic should decrease beyond this region. One can study the impact of this model on the schemes presented in this thesis.

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Appendix A

Residual life theorem

Let X be the random variable denoting call holding time of a mobile and Y be the random variable denoting residual life of the call after crossing the cell coverage. If X is distributed with pdf $f_X(x)$ and Laplace transform $f^*(s)$, pdf of Y can be written as:

$$f_Y(y) = \frac{1 - F_X(x)}{m} \tag{A.1}$$

where $F_X(x)$ is the cdf of X and m is the mean of X.

$$m = \int_0^\infty f_X(x)\,dx \tag{A.2}$$

If $\hat{f}^*(s)$ is The Laplace transform of random variable Y, (A.1) can be transformed as:

$$\hat{f}^*(s) = \frac{1 - f^*(s)}{s.m} \tag{A.3}$$

Appendix B

Markov Modulated Poisson Process (MMPP)

MMPP is a doubly stochastic process, where the rate process is determined by the state of a continuous time Markov chain. Consider two state MMPP where the rates of exiting states 1 and 2 are r_1 and r_2 respectively. When the chain is in state j (j = 1,2), the arrival process is Poisson with rate λ_j.

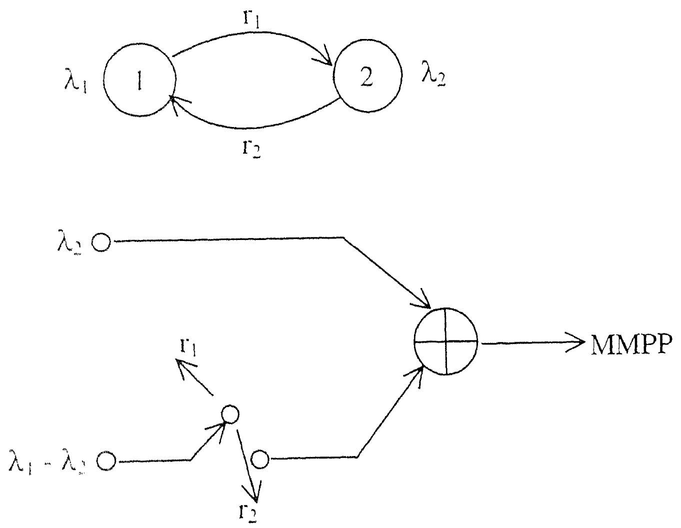

Fig B.1 Representation of MMPP

Fig B.1 represents the equivalence between this process and superposition of a Poisson and an interrupted Poisson process (IPP). IPP is a special case of two state MMPP in which rate in one of the states is null.

Let $\Pi = [\Pi_1 \quad \Pi_2]$ be the row vector of equilibrium probabilities for the state of the MMPP and Λ the diagonal matrix of Poisson intensities A. Λ and A is given by:

$$\Lambda = \begin{bmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{bmatrix} \quad \text{and} \quad A = \begin{bmatrix} -r_1 & r_1 \\ r_2 & -r_2 \end{bmatrix}$$

Then Π is given by:

$$\Pi = [\Pi_1 \quad \Pi_2] = \frac{1}{r_1 + r_2}[r_2 \quad r_1]$$

Mean arrival rate is given by;

$$m = \lambda_1 \Pi_1 + \lambda_2 \Pi_2 = \frac{\lambda_1 r_1 + \lambda_2 r_2}{r_1 + r_2}$$

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